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NEW TECHNOLOGIES FOR MONITORING NUCLEAR MATERIALS*

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ABSTRACT

New technologies for monitoring the continued presence of nuclear materials are being evaluated in Oak Ridge, Tennessee, to reduce the effort, cost, and employee exposures associated with conducting nuclear material inventories. These technologies also show promise for the international safeguarding of process systems and nuclear materials in storage, including spent fuels. The identified systems are based on innovative technologies that were not developed for safeguards applications. These advanced technologies include passive and active sensor systems based on optical materials, inexpensive solid-state radiation detectors, dimensional surface characterization, and digital color imagery. The passive sensor systems use specialized scintillator materials coupled to optical-fiber technologies that not only are capable of measuring radioactive emissions but also are capable of measuring or monitoring pressure, weight, temperature, and source location. Small, durable solid-state gamma-ray detection devices, whose components are estimated to cost less than $25 per unit, can be implemented in a variety of configurations and can be adapted to enhance existing monitoring systems. Variations in detector design have produced significantly different system capabilities. Dimensional surface characterization and digital color imaging are applications of developed technologies that are capable of motion detection, item surveillance, and unique identification of items.

INTRODUCTION

Current domestic and international policies are forcing safeguards organizations to operate under constant or decreasing operating budgets. In addition, the organizations must adapt to new programmatic missions at their sites, some of which demand increased effort from the safeguards staffs. At many U.S. Department of Energy (DOE) sites the priority is changing from active production activities to long-term storage of special nuclear materials (SNM). To meet the safeguards requirements with existing staffs, safeguards organizations are evaluating changes in their operating procedures to increase the effective use of their resources. For many material control and accounting (MC&A) organizations, these savings must occur through reductions in the frequency and intensity of physical inventories. Some efficiencies are being gained through stricter segregation of materials according to attractiveness levels and safeguards categories and through maximizing the use of existing protection features.

Recently, DOE issued guidance defining physical inventory period extensions justified by implementation of containment, surveillance, and monitoring capabilities above the baseline levels. These capabilities are segregated into area and environment attributes, location and containment attributes, and item and material attributes.[1] If sufficient verification of location, containment, item, and material attributes is provided, the monitoring and measurement system performs a continuous physical inventory, thus eliminating the need for periodic inventories. In general, and especially for uranium materials, the existing safeguards monitoring technologies are not capable of meeting the continuous physical inventory criteria. Most existing monitoring technologies are designed to verify location or containment of the nuclear material items through the use of electronic sensors. Item attributes are continuously monitored by two systems developed for monitoring plutonium storage (i.e., the Vault Safety and Monitoring System and the METROX system).[2] Low-cost technology for monitoring material attributes (e.g., gamma-ray or neutron emissions from the SNM) is missing from the currently implemented monitoring systems. To effectively meet both the safeguards requirements and the financial constraints imposed on the safeguards organizations, monitoring systems need to be developed that not only extend physical inventory periods, or perform a continuous physical inventory, but also are inexpensive to purchase, install, operate, and maintain.

NEW TECHNOLOGIES

The DOE facilities in Oak Ridge [i.e., Oak Ridge National Laboratory (ORNL), Y-12 Plant, and K-25

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†Managing contractor for the U.S. Department of Energy.

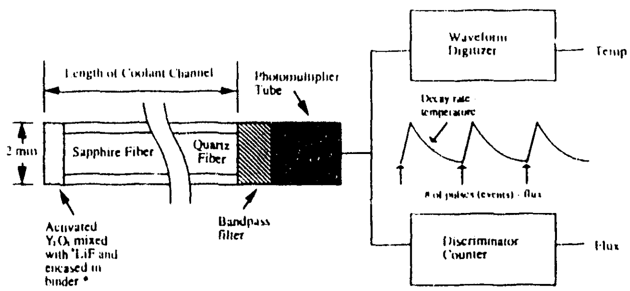
Site] are faced with the probability of rapidly increasing storage requirements for Category I through IV quantities of SNM. Materials in storage include high-enriched uranium (HEU), ^{233}U, plutonium, low-enriched uranium (LEU), irradiated SNM, and other nuclear materials. Storage configurations include tube, port hole, and in-floor vaults; floor, shelf, and rack storage systems; drum and cage storage; security cabinets; pool and tank storage; glove box and hot cell storage; and unique inaccessible storage. The need for new safeguards equipment and approaches to reduce the storage and physical inventory costs for these materials and storage configurations has been recognized.

A "word-of-mouth" survey was initiated at the Oak Ridge facilities to identify technologies that could be developed to reduce the SNM inventory requirements at the facilities. Six technologies at ORNL have been identified to date that have the potential to address the identified safeguards needs: (1) scintillator materials coupled to optical-fiber systems, (2) silicone-rubber optical-fiber systems, (3) silicon PIN solid-state radiation detectors, (4) scintillator-photoresistor solid-state radiation detectors, (5) dimensional surface characterization, and (6) digital color image processing from a mobile vehicle. These technologies are derived from the following technology areas in which ORNL is recognized internationally for its technical expertise: optical materials, radiation detection, smart skins, robotics, and process systems and system design. Development of the technologies has been funded through DOE and work-for-others programs such as Nuclear Safety (e.g., criticality safety), Energy Research, Environmental Restoration and Waste Management, the Department of Transportation, and the Federal Emergency Management Agency, among others. The identified technologies provide capabilities ranging from augmentation of existing systems through providing a new generation of sensor technology for nuclear material monitoring.

OPTICAL FIBER SENSOR SYSTEMS

ORNL, through its research programs in optical materials, has developed a variety of materials for use in alpha-, beta-, gamma-ray-, and neutron-sensitive scintillator detectors. In addition to sensors for measuring radiation flux, new sensor materials and optical-fiber technologies have been developed that are capable of measuring temperature, weight, pressure, strain, crack formation and propagation, source location, moisture infiltration, state-of-cure, and angle of inclination.[3,4] The optical technologies include optical time-domain reflectometry, scintillating fibers, phosphor-coupled wavelength-shifting fibers, and silicone-rubber optical fibers. To enhance their monitoring capabilities within specific applications, the optical sensors have been embedded in numerous materials (e.g., polyurethanes, rubbers, concrete and cementitious materials, asphalt, silicon carbide, carbon and glass fiber composites, and carpet). Optical-fiber technologies currently are used to transmit information, to provide remote viewing capability (e.g., light scopes), and to provide tamper detection (e.g., VACOSS and Cobra seals). Combining the new optical material technologies with older technologies can provide the capability to remotely, passively, and continuously inventory nuclear materials in a vault.

The optical-fiber technologies have the capability to monitor multiple attributes through one fiber (Fig. 1). An example of a passive sensor for both neutron and temperature measurement is the combination of a thermophosphor (e.g., rare-earth activated Y_2O_3) with ^6LiF (95% ^6Li). This combination results in a new class of scintillators for thermal neutrons that absorb energy from the radiation particles and reemit energy as light, the decay rate of which, over a specified temperature range, is temperature dependent. The neutron flux is measured by the number of detected neutron pulses per unit time.



* This is an example of one possible combination of phosphors which could be used for this application

Fig. 1. Neutron flux and temperature are obtained from fluorescent signals generated by the neutrons

Silicone-rubber optical fibers provide unique monitoring capabilities within the optical materials (Fig. 2). The light transmission of these optical materials varies proportionately with squeezing or stretching of the fiber. This technology has been deployed as a weigh-in-motion scale for trucks and as a roadway-use monitor. Additionally, it has been applied to weight sensing pads and other detection systems and is applicable to any monitoring system containing components that would compress or stretch the optical fiber. Because the system continuously transmits light and detects changes in the light transmission, it is self-testing.

The optical-fiber technologies should be applicable to many safeguards applications. These sensor materials provide completely passive, remote measurement capability. No power supplies, amplifiers, or other active components are required at the sensor location that could degrade system reliability.

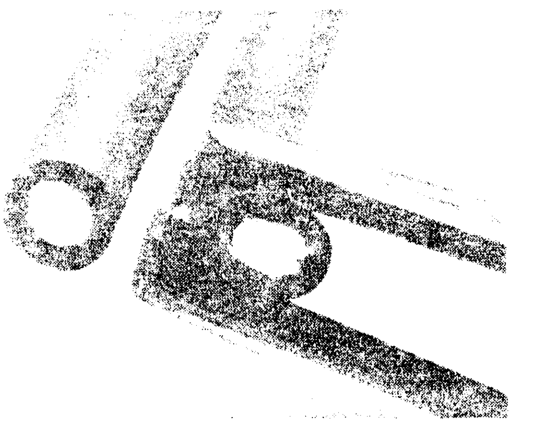


Fig. 2. Silicon-rubber optical fiber

For SNM storage applications, a "smart-mat" has been designed that combines multiple optical-fiber technologies into a mat on which the containers of SNM would sit (Fig. 3). The light from the scintillator materials of each sensor set would be sent through an optical-fiber bundle to the monitoring station where the attribute quantities would be quantified. The sensors also could be implemented individually to form other monitoring and measurement systems. Gamma-ray- or neutron-sensitive optical materials could be deployed on the header pipes of enrichment cascades to continuously monitor the absence of HEU production. Transmission of the light signal would be transferred through the tamper-resistant fiber-optic lines to the monitoring station where one electronic package could monitor many cascades. The fiber-optic systems also could provide the capability to perform remote measurements of irradiated materials. For example, the neutron, gamma-ray, and temperature measurement capabilities could be combined into a small fiber bundle that could be inserted into a spent fuel assembly to verify its burnup without disturbing the fuel assembly. These optical fibers also could be combined with a fiber-optic light scope system capable of measuring the intensity of the Cerenkov glow. The optical-fiber sensors also could be built into spent fuel storage systems to monitor temperature and neutron flux for both safety and safeguards purposes.

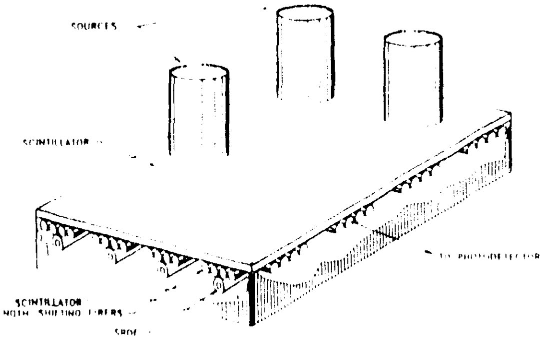


Fig. 3. Generalized smart-mat configuration

SOLID-STATE RADIATION MONITORS

Two different technologies for small, inexpensive, and durable gamma-ray sensor systems capable of confirming the presence of SNM have been developed at ORNL. These systems are (1) the silicon PIN radiation monitor and (2) the scintillator-photoresistor radiation monitor. The first was developed for low-cost personal radiation monitors; the second, for low-cost criticality monitors.

The silicon PIN radiation monitor is composed of low-cost, off-the-shelf microcircuits that combine the low-voltage, reverse-bias photon detector with a low-noise preamplifier, a pulse-shaping amplifier, and a discriminator circuit. The discriminator circuits eliminate spurious noise pulses and low-energy gamma-ray pulses. The system can provide useful count rates from background up to 4 Gy/h radiation levels. Output signals can be locally displayed or cabled to a central data station and analyzed; in addition, each unit could contain a counting rate meter to facilitate on-site checks and maintenance. The system is small (i.e., 1 × 2 × 4 cm), rugged, highly sensitive, and low cost. The detector chip (Fig. 4) costs less than $10, and the detector, plus all supporting electronics to produce a recordable signal, costs less than $25. All detection and electronic components are commercially available.

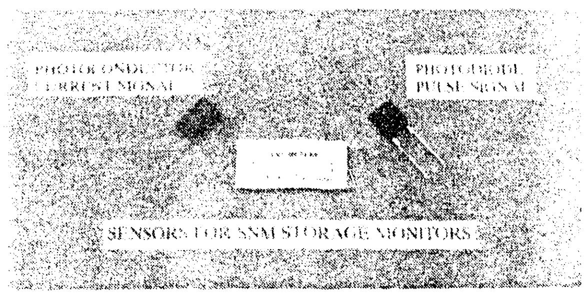


Fig. 4. Sensors for SNM storage monitors

The scintillator-photoresistor radiation monitor consists of a photoresistor coupled to a small CsI(Tl) scintillator crystal. The system uses simple, low-voltage direct-current electronics and produces an electrical output proportional to the gamma-ray flux. An operational amplifier at the sensor converts the photodetector signal current to a voltage and provides adjustable signal amplification. Through use of a light-emitting diode mounted on the crystal, remote testing of each sensor is permitted. The lifetime of the sensors is expected to be comparable to that of currently projected storage facilities with little or no maintenance required. The sensors are small (i.e., 0.5 cm diam by 1 cm long) and inexpensive and can be deployed with one detector on each item to be monitored. The detector head components, when bought in quantity, cost less than $3; the detector head, plus all supporting electronics to produce a recordable signal, costs less than $10. All components are commercially available.

The small, inexpensive solid-state radiation detectors should be applicable to many safeguards applications. The sensors could be monitored individually or as a string of sensors combined in parallel. If deployed individually, they could be powered from either a central power supply or a small battery. The detector could operate as a companion to, or component of, the WATCH or AIMS systems and transmit radiation levels to a receiver unit.[2] The detector unit can be separated from the sensor electronics and placed in rods or arrays within the storage area while maintaining most electronics outside the measurement area. The sensors provide stable readings of radiation levels and fast response not only to the removal of stored material but also to the introduction of material. This capability also would permit them to be used as radiation sensors in portals, passageways, tanks, and pipes to detect both the presence of radioactive materials and the direction of motion of the materials. These detectors also could be deployed on the header pipes of enrichment cascades to continuously monitor the absence of HEU production.

DIMENSIONAL SURFACE CHARACTERIZATION

ORNL had developed surface mapping and surface characterization systems that operate on both macro- and microscopic scales. These systems gather range data using the principle of structured light.[5] The measurement process is noncontact and uses a planar laser, video cameras, and computer components. Measurements are obtained under computer control. The sensor characterizes volumetric regions by generating a large set of 3-D spatial measurements, which are dense, accurate, and rapidly obtained, across surfaces of interest. Figure 5 depicts ORNL's Surface Characterization and Object Pose Equipment (SCOPE) developed for use with small-scale applications. SCOPE's objective is to automatically combine both range and color data to fit geometric models to scanned objects. The system has been designed for automated in situ calibration.[6]

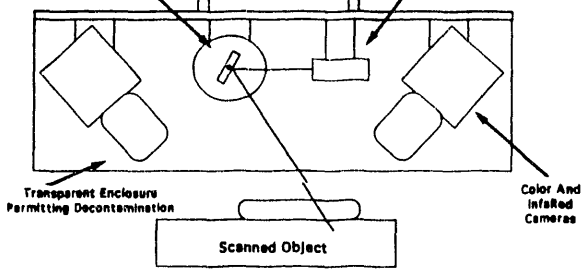


Fig. 5. SCOPE schematic

The parent system to SCOPE was deployed at the Fernald Site to map the distribution of solid waste materials in the interior of an underground 80-ft-diam waste storage silo. The technique has since been adapted for mapping surfaces within the waste tanks at Hanford. The system was capable of determining distances within the Fernald silo to within 2 in. The SCOPE system, in its current demonstration mode, has been capable of measuring surface features of <0.001 ft from a standoff distance of 1 ft. The SCOPE system is directed at applications within automated glove boxes, requiring high-speed mapping of object position and surface characteristics.

The technology can be optimized for surveillance of HEU storage vaults, measurement of SNM holdup in glove boxes, or assessment of containers in waste storage yards. The system is capable of both verifying the position of items and identifying objects by their surface features. The system could be deployed to characterize the placement of items in a room by their measured distances from the detector and to compare this record against previous records. Also, the system could be used to examine items in storage to verify unique physical characteristics (of weld seams or scratches in addition to dimensions) or unique identifiers affixed to the item. In addition to these uses, the system could function as a motion detector, comparing the measured distances from the detector head to the observed surface and detecting any changes in the distances that would be caused by the presence of an intruder. The camera component of the SCOPE system would then be capable of supporting immediate assessment of the alarm. The capabilities of the system and its mode of operation would be dependent on the needs of the specific use.

DIGITAL COLOR IMAGE PROCESSING

Digital image processing has been developed and implemented for surveillance in SNM storage vaults.[2] The system is installed in relatively small vaults and uses fixed camera angles. The monitoring algorithms react to any change in the vault condition from the reference image. ORNL has been developing color digital image processing for the DOE Office of Environmental Restoration and Waste Management to automate inspection of the integrity of barrels at waste storage facilities. The storage areas of concern contain tens of thousands of barrels, each of which must be inspected on a regular basis. Thus, the camera and processors must be located on a mobile vehicle. The Remote User Survey Tool (RUST) system is designed to analyze color images acquired from the remote vehicle and to report items with potential problems to the control station. The system digitally compares the color and texture of the image from an item to the previously recorded image to detect the growth of rust spots or the presence of leaking material. The system provides the capability to uniquely identify an item by using a digital image processor located on a moving platform. The system performs anomaly analysis in real-time (i.e., camera frame rates) using commercially available equipment.

RUST could be adapted for use as a safeguards system to monitor SNM in storage. The system extends the technology currently used in vault surveillance by providing the capability to perform image processing with algorithms that accommodate camera positioning in the verification of individual drum characteristics. Because RUST is being designed for use in outdoor environments, it could easily be modified for indoor applications. RUST provides the capability to remotely inventory items in large physical arrays or in arrays that do not permit observation of all items from a few camera angles. From the robotic platform, the image processor can be maneuvered to a position from which it can verify unique characteristics of the stored items. Surface irregularities such as weld signatures or unique markings (e.g., colored paint splatters or iridescent optical fibers) could be item parameters monitored to detect unauthorized activities. In addition to providing the item recognition capability for taking physical inventory, the system also could provide the motion detection and item movement detection capabilities provided by current fixed-position digital image processing systems.

SUMMARY

Six technologies derived from technology areas in which ORNL is recognized internationally for its technical expertise have been identified. These technologies, which have the potential to address safeguards monitoring needs for long-term storage of SNM, are: (1) scintillator materials coupled to optical-fiber systems, (2) silicone-rubber optical-fiber systems, (3) silicon PIN solid-state radiation detectors, (4) scintillator-photoresistor solid-state radiation detectors, (5) dimensional surface characterization, and (6) digital color image processing from a mobile platform. The capabilities of these technologies are summarized in Table 1. The installation requirements of each system are identified as medium because the systems require wiring the vault but not significant vault reconstruction.

Glass and silicone-rubber optical fibers are capable of being combined with other optical materials and optical technologies to provide systems that are capable of monitoring all item attributes potentially of importance for conducting a continuous physical inventory, as well as for providing area and containment monitoring. The fiber-optic systems would be passive and extremely rugged within the vault area. All electronic components requiring maintenance would be located outside the vault in a protected but accessible area; thus, maintenance of the system would not require access to the vault. Optical-fiber systems may define the future state-of-the-art systems for vault monitoring.

Small, inexpensive solid-state radiation detectors may extend the capability of existing SNM monitoring systems so that they may become capable of providing continuous physical inventories. The low cost of these detectors will permit the placement of detectors on each item in inventory and will permit continuous monitoring of the gamma-ray radiation levels from the item. These systems also have applications to process monitoring.

Digital color image processing and dimensional surface characterization provide new technologies to extend the capabilities of existing vault surveillance systems. Existing digital vault surveillance systems are designed to provide motion detection or item movement detection from a fixed location. The two new technologies provide not only these capabilities but also the capability to uniquely identify items in the inventory. Both technologies can be mounted on robotic platforms thus permitting observation of all items through movement of the systems as necessary. Because both systems are based on different scientific principles, the systems offer different capabilities to defeat potential adversary strategies.

More extensive probing of ORNL research and development programs is expected to unveil additional proven technologies that can be adapted to meet safeguards needs. It is anticipated that proven technologies that have been developed for other programs but that are applicable also to safeguards needs can be found on most DOE sites.

REFERENCES

1. G. L. McFadden, letter to distribution, "Guidance and Criteria for Reducing Nuclear Material Physical Inventory Requirements," U.S. Department of Energy, Washington, D.C., July 21, 1992.
2. J. A. Abbott and I. G. Waddoups, *Technologies for Item Monitoring*, SAND93-0573, Sandia National Laboratories, Albuquerque, August 1993.
3. S. A. McElhaney, et al., *Passive (Self-Powered) Fiber Optic Sensors*, pp. 101–103 in conference record of the 1992 IEEE Nuclear Science Symposium and Medical Imaging Conference, Orlando, October 25–31, 1992.
4. J. D. Muhs, "Silicone Rubber Fiber Optic Sensors," pp. 98–102 in *Photonics Spectra*, July 1992.
5. B. L. Burks, et al., *Waste Surface Mapping of the Fernald K-65 Silos Using a Structured Light Measurement System*, ORNL/TM-12185, Oak Ridge Natl. Lab., Oak Ridge, Tenn., September 1992.
6. F. DePiero and R. Kress, *Camera Calibration in a Hazardous Environment Performed in Situ with Automated Analysis and Verification*," pp. 109–115 in proceedings of the ANS 5th Topical Meeting on Robotics and Remote Systems, Knoxville, April 26–29, 1993.

Table 1. Item monitoring technology comparison

System	Use	Vault access	Item presence	Item identity	Weight	Temperature	Radiation presence	Radiation quantity	Isotopics	Passive (no electronics) sensor head	Installation requirements
Fiber-optic sensors											
a. Location	Position monitoring	No	Yes	No	No	No	Yes	No	No	Yes	Medium
b. Radiation	Radiation monitoring	No	Yes	No	No	No	Yes	Yes	Yes	Yes	Medium
c. Temperature	Temperature monitoring	No	Yes	No	No	Yes	Yes	No	No	Yes	Medium
d. Weight	Weight monitoring	No	Yes	No	Yes	No	No	No	No	Yes	Medium
e. Pressure	Presence monitoring	Yes	Yes	No	Yes	No	No	No	No	Yes	Medium
f. Optical scope	Identification monitoring	No	Yes	Yes	No	No	Yes, if Cerenkov glow	No	No	Yes	Medium
Fiber-optic mat (smart-mat)	Position and attributes monitoring	No	Yes	No	Yes	Yes, if neutron	Yes	Yes	Yes, if gamma ray	Yes	Medium
Solid-state detector system	Radiation monitoring	No	Yes	No	No	No	Yes	Yes	Maybe	No	Medium
Solid-state scintillator sensor system	Radiation monitoring	No	Yes	No	No	No	Yes	Yes	No	Yes	Medium
Surface mapping and inspection	Item verification	Yes	Yes	Yes	No	No	No	No	No	No	Medium
Digital image processing	Item verification	Yes	Yes	Yes	No	No	No	No	No	No	Medium

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